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Visual memories for perceived length are well preserved in older adults

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ABSTRACT

Three experiments compared younger (mean age was 23.7 years) and older (mean age was 72.1 years) observers' ability to visually discriminate line length using both explicit and implicit standard stimuli. In Experiment 1, the method of constant stimuli (with an explicit standard) was used to determine difference thresholds, whereas the method of single stimuli (where the knowledge of the standard length was only implicit and learned from previous test stimuli) was used in Experiments 2 and 3. The study evaluated whether increases in age affect older observers' ability to learn, retain, and utilize effective implicit visual standards. Overall, the observers' length difference thresholds were 5.85% of the standard when the method of constant stimuli was used and improved to 4.39% of the standard for the method of single stimuli (a decrease of 25%). Both age groups performed similarly in all conditions. The results demonstrate that older observers retain the ability to create, remember, and utilize effective implicit standards from a series of visual stimuli.

1. Introduction

Among the many psychophysical methods developed by Gustav Fechner (1860/1966), the method of constant stimuli (originally called the method of right and wrong cases) is quite straightforward: on any given trial, a participant is presented with two stimuli (one possesses a "standard" value that remains fixed throughout a block of trials while the value of the other varies) and is required to judge which of the two stimuli is heavier, longer, brighter, louder, etc. In this method the participant compares each of the "test" stimuli with the explicitly presented standard stimulus. Such judgments are often used to calculate difference thresholds. As early as 1899, however (Martin and Müller, 1899; also see Fernberger, 1931; McKee, 1981; McKee & Welch, 1985; Morgan, Watamaniuk, & McKee, 2000; Nachmias, 2006; Norman et al., 2008; Norman & Todd, 1998; Pfaffmann, 1935; Wever & Zener, 1928), it was demonstrated that participants could effectively compare singly presented stimuli with an "implicit" or "mental" standard that was derived from a series of previous stimuli. In other words, participants can make "absolute judgments" about single stimuli in a manner that is as accurate as when an explicit comparison stimulus is available.

The fact that human participants can make accurate comparisons between the magnitudes of singly presented perceptual stimuli and a purely implicit standard stimulus (no explicit standard is ever presented) requires that the value of this implicit standard be "kept in mind" (i.e., stored in memory). The results of Morgan, Watamaniuk, and McKee (2000) suggest that human participants derive their knowledge of an implicit standard from the running average of the test stimuli encountered over the most recent 10–20 trials. They state (p. 2347) "our results show that well-trained observers can estimate and store an accurate representation of stimulus parameters by sampling stimulus information over as many as 20 trials." It is well known that aging leads to significant decline in various forms of memory (e.g., Giambra et al., 1995; Hedden & Gabrieli, 2004; Miller et al., 2008; Small et al., 1999). Does aging lead to declines in this form of perceptual memory? Can older adults form and maintain accurate implicit standards from a series of perceptual stimuli or do they need the presence of explicit standards in order to make accurate judgments? At the moment, the answers to such questions are entirely unknown – no research has ever investigated such issues. The purpose of the current study was straightforward: to evaluate older adults' abilities to form, maintain, and utilize an implicit perceptual standard. In the current study, the purpose of Experiment 1 was to determine baseline performance when explicit standards are available. In Experiments 2 and 3, the explicit standards were removed, and the observers were forced to judge the test stimuli relative to an implicit standard.

2. Experiment 1

2.1. Method

2.1.1. Apparatus

The stimulus displays were generated by an Apple PowerMacintosh G4 computer and were presented on a 22-in. Mitsubishi

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Diamond Plus 200 monitor. The resolution of the monitor was 1280 × 1024 pixels. The viewing distance between the observers and the monitor was 100 cm.

2.1.2. Experimental stimuli

The experimental stimuli were white lines presented (in the frontoparallel plane) against a black background. The standard line was 9.0 cm long (same as the standard used in Experiment 1 of Norman et al. (1996)), and it subtended 5.2° visual angle. There were a total of six test lengths, three of which were physically longer than the standard (by 1.6%, 4.8%, and 8.0%) and three that were shorter than the standard (also by 1.6%, 4.8%, and 8.0%).

2.1.3. Procedure

In this experiment, the standard length was explicitly presented on each trial (method of constant stimuli, MCS). A sequential two alternative forced-choice (2AFC) procedure was used (e.g., see Nachmias, 2006; Norman et al., 2008): whether the standard or test length was presented first was randomly determined for each trial. On any given trial the two stimuli were presented for 2.0 s each, separated by an inter-stimulus interval (ISI) of 1.5 s. The observers' task was to judge which of the two lines was longer, the first or the second. Each line possessed a random orientation and was randomly offset from the center of the display (both horizontally and vertically) by up to 5 cm (2.9° visual angle). No feedback was given to the observers. For each observer, two experimental blocks were completed. Each block consisted of 150 trials (6 test lengths × 25 trials/test length). The order of the test lengths within a block was randomly determined. At the end of the experiment, therefore, each observer had judged a total of 300 test lengths (2 blocks of trials × 150 trials/block).

2.1.4. Observers

Twenty younger and older adults participated in the experiment. Ten of the participants were 69 years of age or older (mean age was 74.0 years, SD = 4.8; ages ranged from 69 to 82 years), while another 10 observers were 27 years of age or younger (mean age was 23.7 years, SD = 2.4; ages ranged from 19 to 27 years). All observers were naive with respect to the nature and purpose of the experiment. All of the observers possessed normal, or corrected-to-normal, visual acuity (acuity was tested at a viewing distance of 100 cm).

2.2. Results and discussion

Representative results of the experiment can be seen in Fig. 1, which plots data and best-fitting psychometric functions for typical younger and older adults. To determine the observers' difference thresholds, we fit a cumulative normal to each observer's data and halved the difference between the 75th and the 25th percentage points of the observer's psychometric function (e.g., see Engen, 1971; Westheimer & McKee, 1977). The average difference thresholds were 5.4% and 6.3% of the standard for the older and younger observers, respectively (standard deviations were 1.44 and 1.08, respectively). In other words, the observers needed a difference in length of 5–6% in order to reliably detect which of the two lines (presented on any given trial) was longer. There was no significant difference in performance between the two age groups ($t(18) = -1.6$, $p = .13$, 2-tailed). It is important to keep in mind that while there was no significant difference between the age groups, the older observers' performance was numerically superior (lower difference thresholds reflect better discrimination performance).

Most of the previous studies evaluating the visual discrimination of (2-D) line lengths have asked observers to compare parallel lengths (e.g., Creelman, 1965; Lapid, Ulrich, & Rammsayer, 2009; Maxfield, 1913; Stevenson, 1918; Weber, 1834/1996, pp. 103–105). The difference thresholds (i.e., Weber fractions) obtained in these studies ranged from 1% to 5% of the standard length. The difference thresholds obtained in the current experiment for our younger and older observers were slightly higher, but this result is not surprising because Norman et al. (1996, see Experiment 1) previously found difference thresholds for discriminations of randomly-oriented lengths to be 37% greater than those for parallel lengths.

3. Experiment 2

The results of Experiment 1 clearly demonstrate that older adults perform just as well at discriminating lengths as younger adults when an explicit standard stimulus was available to serve as a reference (i.e., on any given trial, the observers saw two explicitly presented lines and had to indicate which of the two was longer). As discussed in Section 1, it has been known for more than one hundred years that younger adults can learn a "mental" or implicit standard stimulus and then effectively compare subsequent single test stimuli with it. The ability to perform such comparisons requires that the observer store and maintain a representation of the implicit standard stimulus in perceptual memory for extended periods of time. Ordinary adults are so good at this implicit task (method of single stimuli) that their performance is at least as good as that obtained in the method of constant stimuli where explicit standard stimuli are presented (e.g., see Nachmias, 2006; Norman et al., 2008). At present, it is not known whether older adults can effectively create and utilize implicit perceptual standards: the purpose of Experiment 2 is to fill this void.

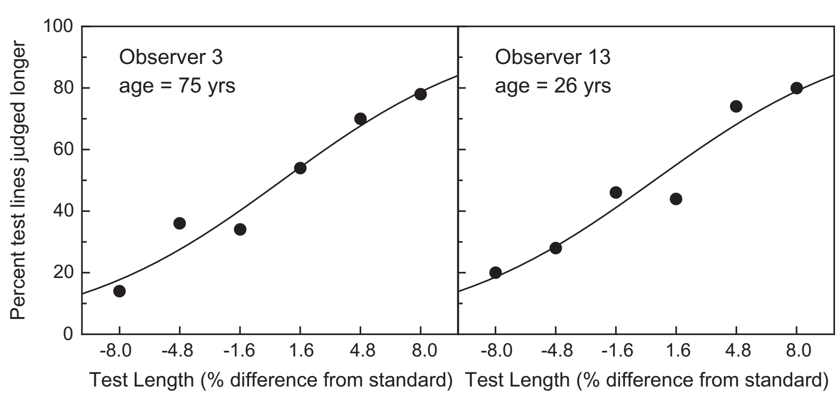

Fig. 1. Results of Experiment 1 (method of constant stimuli). Data and best-fitting psychometric functions are illustrated for representative younger and older observers. The percentages of test lines judged to be longer than the standard are plotted for the six test lengths. The negative test lengths are physically shorter than the standard (by 1.6%, 4.8%, and 8.0%), while the positive test lengths are physically longer than the standard (by 1.6%, 4.8%, and 8.0%).

3.1. Method

3.1.1. Apparatus and experimental stimuli

The apparatus, experimental stimuli, and viewing distance were identical to those used in Experiment 1.

3.1.2. Procedure

In this experiment, the method of single stimuli (MSS) was used to measure the younger and older observers' length difference thresholds. Only a single test length was presented on each trial (as was done in Experiment 1, these single lengths randomly varied in orientation and position across trials). The observers' task was to judge whether each individual test length was longer or shorter than the implicit standard (which was never physically presented). The observers were required to learn the magnitude of the implicit standard at the beginning of an experimental block from a series of 20 practice trials, where they received auditory feedback (a short beep) for correct responses. After these 20 practice trials, the observers had a good impression of the implicit standard (Morgan, Watamaniuk, & McKee, 2000; Norman & Todd, 1998; Norman et al., 2008). Following this establishment of the implicit standard, the feedback was either continued throughout the rest of an experimental block of trials in one experimental condition (MSS with feedback), while it was discontinued for the other experimental condition (MSS without feedback). In previous investigations, identical results have been obtained for the method of single stimuli regardless of whether feedback was, or was not, provided (Morgan, Watamaniuk, & McKee, 2000; Vogels & Orban, 1986). Nevertheless, since the presence or absence of feedback could conceivably affect the discrimination performance of the older observers, we decided to measure the observers' thresholds with and without feedback.

For each of the two conditions (MSS with feedback, MSS without feedback), two experimental blocks were completed. Each block consisted of 150 trials (6 test lengths × 25 trials/test length). The order of the test lengths within a block was randomly determined. At the end of the experiment, therefore, each observer had judged a total of 600 test lengths (2 conditions × 2 blocks of trials/condition × 150 trials/block).

3.1.3. Observers

The 20 younger and older observers were the same as those who had participated in Experiment 1. All observers had normal, or corrected-to-normal, visual acuity.

3.2. Results and discussion

Representative data and psychometric functions for the method of single stimuli with feedback are shown in Fig. 2 for typical younger and older observers. All of the observers' difference thresholds (for both MSS conditions) are shown in Fig. 3, along with their analogous MCS thresholds from Experiment 1. The difference thresholds for individual observers are indicated by the filled circles, while the open circles indicate the observers' mean thresholds for the various age groups and conditions. As can be clearly seen, there was absolutely no effect of age in the current experiment ($F(1, 18) = 0.0004$, $p = .98$). An analysis of variance conducted upon the thresholds shown in Fig. 3, however, did reveal a significant main effect of experimental method ($F(2, 36) = 15.3$, $p < .0001$, partial $\eta^2 = .46$). The observers' difference thresholds for the method of constant stimuli were 27.9% higher than those obtained for the method of single stimuli. Superior discrimination performance for the method of single stimuli has also been obtained in previous investigations (e.g., see Nachmias, 2006; Norman & Todd, 1998). The age × experimental method interaction was not significant ($F(2, 36) = 1.83$, $p = .18$); if the age × method interaction had been significant it would have been due to the fact that the older observers' performance was slightly higher (i.e., better) in the conditions using the method of constant stimuli. In our experiment, we found no difference in the observers' performance between the MSS conditions that

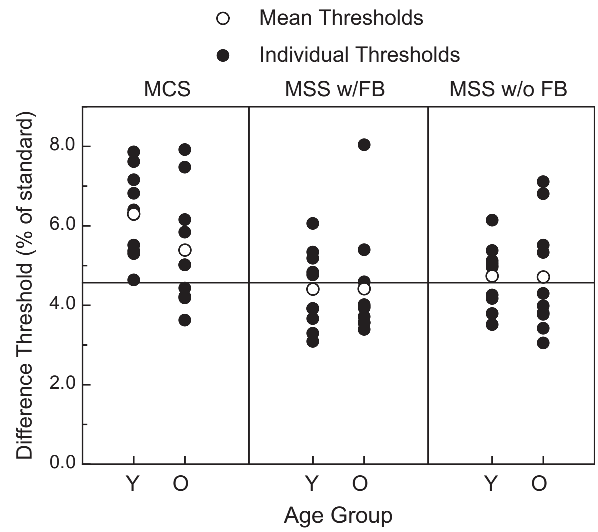

Fig. 3. Results of Experiment 2 (method of single stimuli, MSS), with the analogous results for Experiment 1 (method of constant stimuli, MCS) plotted for comparison. The filled circles represent the difference thresholds for the individual younger (Y) and older (O) observers. The open circles indicate the mean thresholds for the various combinations of experimental method and age group. The horizontal line indicates the average performance obtained in the MSS conditions.

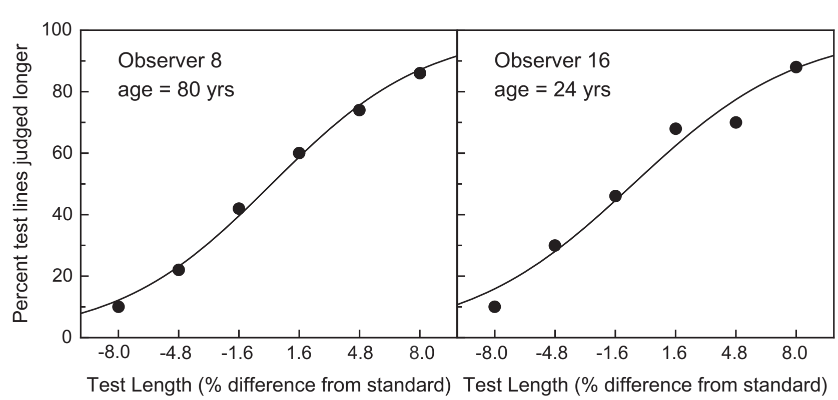

Fig. 2. Results of Experiment 2 (method of single stimuli with feedback). Data and best-fitting psychometric functions are illustrated for representative younger and older observers. The percentages of test lines judged to be longer than the standard are plotted for the six test lengths. The negative test lengths are physically shorter than the standard (by 1.6%, 4.8%, and 8.0%), while the positive test lengths are physically longer than the standard (by 1.6%, 4.8%, and 8.0%).

did and did not provide feedback. This result is analogous to that obtained by Morgan, Watamaniuk, & McKee (2000), who also found equivalent MSS thresholds for feedback and no-feedback conditions.

4. Experiment 3

The results of Experiment 2 showed that both the younger and older observers precisely discriminated the single test lengths even when the standard length was not explicitly presented within any block of trials. However, all of those observers had previously participated in Experiment 1 (method of constant stimuli), when they had been able to see the standard length explicitly. It is thus conceivable that the observers' judgments in Experiment 2 could have been influenced by the prior experience they had in Experiment 1 (although this would also demonstrate that our younger and older observers' visual memories are relatively accurate and long lasting!). The purpose of Experiment 3 was to conduct an even more stringent test of older adults' abilities to learn, remember, and utilize implicit standard lengths from a series of test stimuli. In this experiment, new naïve older observers were recruited who had never seen the standard lengths explicitly under any circumstances (i.e., had never participated in the method of constant stimuli).

4.1. Method

4.1.1. Apparatus and experimental stimuli

The apparatus, experimental stimuli, and viewing distance were identical to those used in Experiment 2.

4.1.2. Procedure

In this experiment, the method of single stimuli (with feedback) was again used to measure the older observers' length difference thresholds. A single randomly-oriented test length was presented on each trial. The observers' task was to judge whether each individual test length was longer or shorter than the implicit standard (which was never physically presented). As in Experiment 2, the observers were required to learn the magnitude of the implicit standard at the beginning of an experimental block from a series of 20 practice trials, where they received auditory feedback (a short beep) for correct responses. Two experimental blocks were completed by each observer. Each block consisted of 150 trials (6 test lengths $\times$ 25 trials/test length). The order of the test lengths within a block was randomly determined. At the end of the experiment, each observer had judged a total of 300 test lengths (2 blocks of trials $\times$ 150 trials/block).

4.1.3. Observers

Five older adults participated in the experiment. They were 65 years of age or older (mean age was 68.2 years, SD = 3.1; ages ranged from 65 to 72 years). All of the observers were completely naive and did not previously participate in either Experiment 1 or Experiment 2. All of the new observers possessed normal, or corrected-to-normal, visual acuity (acuity was tested at a viewing distance of 100 cm).

4.2. Results and discussion

A representative psychometric function for one of the older observers is shown in Fig. 4 (compare with the left panel of Fig. 2). Once again, length difference thresholds were estimated from the observers' psychometric functions. The observers' difference thresholds averaged 3.69% of the standard; they ranged from 2.7% to 5.2%. The older observers' difference thresholds in the current experiment were not significantly different ($t(4) = -1.73$, $p = .16$, 2-tailed) from the analogous threshold (4.42%) obtained in Experiment 2. These results conclusively demonstrate that older observers can learn and retain an implicit standard from a series of test stimuli, and then effectively compare the lengths of single test lengths with it. It is important to remember that the older observers in this experiment did not participate in Experiment 1, and thus never explicitly saw the standard stimulus.

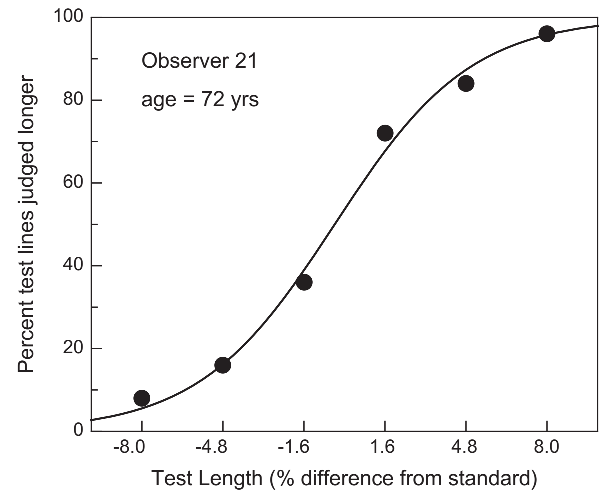

Fig. 4. Results of Experiment 3 (method of single stimuli with feedback). Data and the best-fitting psychometric function are illustrated for a representative older observer (Observer 21, age = 72 years). The percentages of test lines judged to be longer than the standard are plotted for the six test lengths. The negative test lengths are physically shorter than the standard (by 1.6%, 4.8%, and 8.0%), while the positive test lengths are physically longer than the standard (by 1.6%, 4.8%, and 8.0%).

5. General discussion

Past research on both macaque monkeys and humans has demonstrated that aging can have significant effects upon visual memory. For example, Moss, Rosene, and Peters (1988; also see Bachevalier, 1993; Presty et al., 1987; Rapp & Amaral, 1991) required 12 monkeys of various ages, from 4 to 27 years of age, to perform a delayed nonmatching to sample task. On any given trial, the monkeys were shown a single object. Following a delay, the monkeys were then presented with two objects (one novel object and the previously viewed object). The monkeys' task was to select the novel object – this task obviously requires memory for the previously viewed object. In this study, the older monkeys' recognition performance was significantly worse than that of the younger monkeys for all delays. Moss, Rosene, and Peters (1988, p. 499) concluded that "aged rhesus monkeys evidenced an impairment relative to young adult monkeys in the acquisition and performance of a delayed visual recognition memory task".

In human observers, aging has been shown to have adverse effects upon visual memory for a variety of tasks. For example, in a study phase Riege and Inman (1981) presented ten "geometric art patterns" produced by the French artist Victor Vasarely (e.g., see Vasarely, 1965, 1971, 1974, 1979). In a subsequent test phase conducted 1 min later, 120 younger, middle-aged, and older adults were presented with the ten previously viewed images randomly intermingled with similar distractor images; the observers were asked to identify the images that had been previously presented in the study phase. Riege and Inman found significant progressive deteriorations in visual recognition performance as the ages of the observers increased. In 1981, Charness (1981) presented younger and older adults with photographs of chess diagrams that depicted "snapshots" of ongoing chess games (on average, 23 chess pieces were visible). These photographs were presented to the observers for either 1, 2, or 4 s. After a variable delay, the observers were asked to reproduce the previously viewed patterns by populating an empty chess board. Charness found that the older observers' memory for correct piece placement was significantly poorer than that of the younger observers (for a similar finding, see the results of the Pattern Reconstruction task employed by Riege and Inman (1981)). Finally, a large number of investigations of aging and visual memory have employed the Benton Visual Retention Test (BVRT; e.g., see Arenberg, 1978; Coman et al., 1999; Fahle & Daum, 1997; Giambra et al., 1995). On any given trial in the BVRT, observers are shown 2-dimensional geometric diagrams for 10 s; the observers are then required to immediately draw (i.e., reproduce from memory) the pattern that was visually presented. The results from the various investigations are highly consistent, and all demonstrate that the observers' errors in reproduction from memory increase significantly with age (e.g., see Fig. 2 of Giambra et al.).

A number of recent studies have used an oculomotor paradigm to investigate aging and its effects upon memory for visual location. In their memory-guided saccade task (Abel & Douglas, 2007; Burke, Clarke, & Hedley, 2010), participants of different ages were asked to fixate a central target and then attend to the location of a briefly presented target in the periphery. After a variable delay, the fixation stimulus disappeared; the participants' task was to then make a saccade to the remembered location of the target. Abel and Douglas (2007) found that their older participants made more errors than the younger participants and in addition, the latencies of their correct responses were longer. In their conclusions, Abel and Douglas suggested (p. 635) that the age-related failures could involve changes in "working memory capacity". In conditions most resembling those of Abel and Douglas (i.e., the "NoGo/No Frame" condition), Burke, Clarke, and Hedley (2010) found that the precision of their middle-aged (42–58 years of age) participants' saccades was lower than that of their younger participants (i.e., the variability of the older group's saccades was higher than that of the younger group's saccades).

In contrast to the findings of studies that have investigated the visual recall/memory of objects, spatial locations, geometric patterns, and artwork, a sizeable number of recent investigations have found no significant difference between younger and older observers' visual memory. With the exception of studies by Bennett, Sekuler, and Sekuler (2007) and Fahle and Daum (1997), these studies have employed stimuli that were either unidimensional or compound sine-wave luminance gratings (Bennett et al., 2001; Della-Maggiore et al., 2000; McIntosh et al., 1999; Sekuler et al., 2005). In the studies using unidimensional luminance gratings, the younger and older observers' task was to view two successively presented gratings and discriminate which of the two possessed the higher spatial frequency: in all three studies, the older observers performed as well as the younger observers. In the study by Sekuler et al., the younger and older participants viewed two successive compound gratings for 750 ms each, which were followed by a 750 ms probe stimulus at varying delays (1, 2, or 4 s). The observers' task on any given trial was to indicate whether the probe compound grating matched either of the two previously presented gratings. Sekuler et al. found that their older observers' discrimination performance (match versus nonmatch) was as accurate as that exhibited by the younger observers. Sekuler et al. concluded by saying (p. 11) "when visual memory is assayed in healthy older adults tested under conditions that minimize effects of age-related changes in vision, visual recognition memory seems to be unaffected by aging". The study by Fahle and Daum assessed visual short-term memory for observers whose ages ranged from 12 to 66 years. They presented to their observers two successive vernier offsets separated by either 1 or 4 s; the observers' task was to indicate whether the second vernier offset was larger or smaller than the first. The results showed that there were no significant differences between the various age groups. Finally, in the study by Bennett et al. (2007), older and younger observers were shown randomly oriented individual line segments for 500 ms. After a variable delay (0.024–6 s), the observers were required to estimate the orientations of the previously viewed lines. Bennett et al. found no difference in performance between the older and the younger groups of observers, regardless of the magnitude of the delay.

With regards to the findings of the current set of experiments, the results of Experiment 1 demonstrate that when standard lengths are explicitly presented along with the various test lengths (Method of Constant Stimuli), older adults can visually discriminate lengths in a frontoparallel plane as precisely as younger adults. The good performance exhibited by the older observers was impressive, given that our observers' ages spanned a wide range (19–82 years). When the explicit standards were removed in Experiment 2 (also see Experiment 3) and the observers were forced to compare each single test length with an implicitly defined length stored in memory (i.e., MSS, observers compared single test lengths with a learned implicit standard that was never explicitly presented), both age groups performed well. Again, there was no age difference in the precision of length discrimination. Our results are thus similar to, and reinforce the previous findings of Sekuler et al. (2005) and Bennett et al. (2001, 2007) who concluded that visual memory is relatively unaffected by increases in age. Our results are especially interesting, because in the experiments of Sekuler et al. and Bennett et al., their older observers only needed to retain visual information in memory for several seconds in order to make effective judgments for particular trials; in our Experiments 2 and 3 in order to perform well, our older observers had to learn, retain, and utilize an implicit standard length across multiple trials within an overall block of 150.

References

Abel, L. A., & Douglas, J. (2007). Effects of age on latency and error generation in internally mediated saccades. *Neurobiology of Aging, 28*, 627–637.

Arenberg, D. (1978). Differences and changes with age in the Benton visual retention test. *Journal of Gerontology, 33*, 534–540.

Bachevalier, J. (1993). Behavioral changes in aged rhesus monkeys. *Neurobiology of Aging, 14*, 619–621.

Bennett, P. J., Sekuler, A. B., McIntosh, A. R., & Della-Maggiore, V. (2001). The effects of aging on visual memory: Evidence for functional reorganization of cortical networks. *Acta Psychologica, 107*, 249–273.

Bennett, P. J., Sekuler, R., & Sekuler, A. B. (2007). The effects of aging on motion detection and direction identification. *Vision Research, 47*, 799–809.

Burke, M. R., Clarke, J. B., & Hedley, J. (2010). Effect of retinal and/or extra-retinal information on age in memory-guided saccades. *Experimental Brain Research, 205*, 87–94.

Charness, N. (1981). Visual short-term memory and aging in chess players. *Journal of Gerontology, 36*, 615–619.

Coman, E., Moses, J. A., Kraemer, H. C., Friedman, L., Benton, A. L., & Yesavage, J. (1999). Geriatric performance on the Benton visual retention test: Demographic and diagnostic considerations. *The Clinical Neuropsychologist, 13*, 66–77.

Creelman, C. D. (1965). Discriminability and scaling of linear extent. *Journal of Experimental Psychology, 70*, 192–200.

Della-Maggiore, V., Sekuler, A. B., Grady, C. L., Bennett, P. J., Sekuler, R., & McIntosh, A. R. (2000). Corticolimbic interactions associated with performance on a short-term memory task are modified by age. *Journal of Neuroscience, 20*, 8410–8416.

Engen, T. (1971). Psychophysics I: Discrimination and detection. In J. W. Kling & L. A. Riggs (Eds.), *Woodworth & Schlosberg's experimental psychology* (3rd ed., pp. 11–46). New York: Holt, Rinehart, & Winston.

Fahle, M., & Daum, I. (1997). Visual learning and memory as functions of age. *Neuropsychologia, 35*, 1583–1589.

Fechner, G. (1966). *Elements of psychophysics* (H.E. Adler, Trans.) (Vol. 1). New York: Holt, Rinehart, & Winston (Original work published 1860).

Fernberger, S. W. (1931). On absolute and relative judgments in lifted weight experiments. *American Journal of Psychology, 43*, 560–578.

Giambra, L. M., Arenberg, D., Zonderman, A. B., Kawas, C., & Costa, P. T. (1995). Adult life span changes in immediate visual memory and verbal intelligence. *Psychology and Aging, 10*, 123–139.

Hedden, T., & Gabrieli, J. D. E. (2004). Insights into the ageing mind: A view from cognitive neuroscience. *Nature Reviews Neuroscience, 5*, 87–96.

Lapid, E., Ulrich, R., & Rammsayer, T. (2009). Comparisons of two variants of the method of constant stimuli for estimating difference thresholds. *Swiss Journal of Psychology, 68*, 189–192.

Martin, L. J., & Müller, G. E. (1899). *Zur Analyse der Unterschiedsempfindlichkeit Experimentelle Beiträge*. Leipzig: J.A. Barth.

Maxfield, F. N. (1913). An experiment in linear space perception. *Psychological Monographs, 15*(3), 1–49.

McIntosh, A. R., Sekuler, A. B., Penpeci, C., Rajah, M. N., Grady, C. L., Sekuler, R., et al. (1999). Recruitment of unique neural systems to support visual memory in normal aging. *Current Biology, 9*, 1275–1278.

McKee, S. P. (1981). A local mechanism for differential velocity detection. *Vision Research, 21*, 491–500.

McKee, S. P., & Welch, L. (1985). Sequential recruitment in the discrimination of velocity. *Journal of the Optical Society of America A, 2*, 243–251.

Miller, S. L., Celone, K., DePeau, K., Diamond, E., Dickerson, B. C., Rentz, D., et al. (2008). Age-related memory impairment associated with loss of parietal deactivation but preserved hippocampal activation. *Proceedings of the National Academy of Sciences, 105*, 2181–2186.

Morgan, M. J., Watamaniuk, S. N. J., & McKee, S. P. (2000). The use of an implicit standard for measuring discrimination thresholds. *Vision Research, 40*, 2341–2349.

Moss, M. B., Rosene, D. L., & Peters, A. (1988). Effects of aging on visual recognition memory in the rhesus monkey. *Neurobiology of Aging, 9*, 495–502.

Nachmias, J. (2006). The role of virtual standards in visual discrimination. *Vision Research, 46*, 2456–2464.

Norman, J. F., Pattison, K. F., Norman, H. F., Craft, A. E., Wiesemann, E. Y., & Taylor, M. J. (2008). The role of explicit and implicit standards in visual speed discrimination. *Perception, 37*, 889–901.

Norman, J. F., & Todd, J. T. (1998). Stereoscopic discrimination of interval and ordinal depth relations on smooth surfaces and in empty space. *Perception, 27*, 257–272.

Norman, J. F., Todd, J. T., Perotti, V. J., & Tittle, J. S. (1996). The visual perception of three-dimensional length. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 173–186.

Pfaffmann, C. (1935). An experimental comparison of the method of single stimuli and the method of constant stimuli in gustation. *American Journal of Psychology, 47*, 470–476.

Presty, S. K., Bachevalier, J., Walker, L. C., Struble, R. G., Price, D. L., Mishkin, M., et al. (1987). Age differences in recognition memory of the rhesus monkey (*Macaca mulatta*). *Neurobiology of Aging, 8*, 435–440.

Rapp, P. R., & Amaral, D. G. (1991). Recognition memory deficits in a subpopulation of aged monkeys resemble the effects of medial temporal lobe damage. *Neurobiology of Aging, 12*, 481–486.

Riege, W. H., & Inman, V. (1981). Age differences in nonverbal memory tasks. *Journal of Gerontology, 36*, 51–58.

Sekuler, R., Kahana, M. J., McLaughlin, C., Golomb, J., & Wingfield, A. (2005). Preservation of episodic visual recognition memory in aging. *Experimental Aging Research, 31*, 1–13.

Small, S. A., Stern, Y., Tang, M., & Mayeux, R. (1999). Selective decline in memory function among healthy elderly. *Neurology, 52*, 1392–1396.

Stevenson, J. A. (1918). Correlation between different forms of sensory discrimination. *Journal of Applied Psychology, 2*, 26–42.

Vasarely, V. (1965). *Vasarely*. Neuchâtel, Switzerland: Éditions du Griffon.

Vasarely, V. (1971). *Vasarely II*. Neuchâtel, Switzerland: Éditions du Griffon.

Vasarely, V. (1974). *Vasarely III*. Neuchâtel, Switzerland: Éditions du Griffon.

Vasarely, V. (1979). *Vasarely IV*. Neuchâtel, Switzerland: Éditions du Griffon.

Vogels, R., & Orban, G. A. (1986). Decision factors affecting line orientation judgments in the method of single stimuli. *Perception & Psychophysics, 40*, 74–84.

Weber, E. H. (1996). *E.H. Weber on the tactile senses* (H.E. Ross & D.J. Murray, Trans.). East Sussex, UK: Erlbaum (UK) Taylor & Francis (Original work published 1834).

Westheimer, G., & McKee, S. P. (1977). Spatial configurations for visual hyperacuity. *Vision Research, 17*, 941–947.

Wever, E. G., & Zener, K. E. (1928). The method of absolute judgment in psychophysics. *Psychological Review, 35*, 466–493.